HOMOPOLAR PULSE WELDING OF RAIL

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ABSTRACT

The homopolar pulse welding process uses a single unidirectional, high current electrical pulse from a homopolar generator to heat the interface between two workpieces in solid contact. When the interface reaches an optimum temperature, forging pressure is applied, and the workpieces coalesce without melting and without use of either a flux or a filler. The weld is completed in from 1 to 2 s. Because current distribution and heat generation can be made uniform throughout the workpiece section, irregular sections such as rails can be welded. Ninety lb_m/yd rail has been welded with the process using a 10 MJ homopolar generator. The welds were excellent metallurgically, but there were fixturing problems with mechanical clamping, alignment, and current delivery. A through-feeding fixture for welding pipe has been designed and built that successfully addresses these fixturing problems, and electrical contacts and clamps for welding rails are presently being designed. A compact system that could serve as the power supply for an in-track rail welding system has recently become commercially available.

INTRODUCTION

The Center for Electromechanics at The University of Texas at Austin (UT-CEM) is a self-supporting research group in the field of engineering development of pulsed electric power hardware. One of its primary goals over the past decade has been the advancement of homopolar generator (HPG) technology, particularly in the specialty areas of bearings, current collection, improved volumetric energy storage density, and fast instrumentation and control. Concurrent with this development, UT-CEM has applied the inherent high current of the inertial HPG discharge pulse to metal joining by the homopolar pulse welding (HPW) process. In this process, the faying surfaces of two workpieces in contact are preferentially heated as the current traverses the associated interfacial voltage gradient. High force is applied to forge the workpieces together when the proper temperature has been reached.

The advantages of the HPW process include a short welding time (from 1 to 2 s, independent of cross-sectional area), uniform heat generation throughout the section, a narrow heat-affected zone, and good strength retention. No filler metal is required, and welding can generally be accomplished in air with no preheating or shielding. Also, flash is minimal and relatively little axial upset is required, thereby minimizing material loss.

This paper discusses the theories of HPG operation and the details of the HPW process. An HPW rail welding project jointly funded by the National Science Foundation (NSF), the Federal Railway Administration (FRA), and the Association of American Railroads (AAR) [1], is reviewed. In this project the ability of an experimental 10 MJ (10-MJ) laboratory HPG to weld AREA 90 A-A high carbon steel rail was successfully demonstrated. There were certain shortcomings in the welding fixture, however, including the techniques used for current delivery and mechanical clamping. More recently, a through-feeding pipe welding fixture intended to address these problems has been designed and built by OIME, Inc., as part of a pipe welding research program with UT-CEM [2]. OIME has designed the tooling necessary to convert this fixture for advanced research in HPW welding of 90 lb/yd rail in conjunction with UT-CEM's 10-MJ HPG. Furthermore, power supplies for field-portable HPW systems manufactured under license from The University of Texas at Austin have recently become commercially available from OIME.

BACKGROUND

In 1972, the Energy Storage Group (ESG) at The University of Texas at Austin was conceived under the joint

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sponsorship of the Departments of Electrical and Mechanical Engineering. The primary objective of the group was to investigate the feasibility of inertial energy storage machines as power supplies for thermonuclear fusion systems. With funding from the Department of Energy, a 5 MJ HPG was designed, built, and tested by ESG in 1974 [3]. This device is shown in Fig. 1.

Although the 5 MJ HPG was designed as a demonstration pulse generator with a peak output current of 150 kA, it proved to be much more durable than expected. After a mechanical overhaul in 1979 [4], the generator was largely devoted to research in industrial applications such as welding and forging billet heating. In these tests, the machine delivered hundreds of discharges, with peak-current levels as high as 560 kA.

In 1977, EGS became a research center, UT-CEM. Since 1978, several sponsored welding and heating research projects have been carried out [5-8].

In 1980, NSF funded a major rebuilding and upgrading of the original 5 MJ HPG to 10 MJ [9]. This upgrading project resulted in a rugged, highly reliable homopolar generator power supply capable of storing 10 MJ and of delivering current pulses of up to 800 kA. The upgraded machine is shown in Fig. 2.

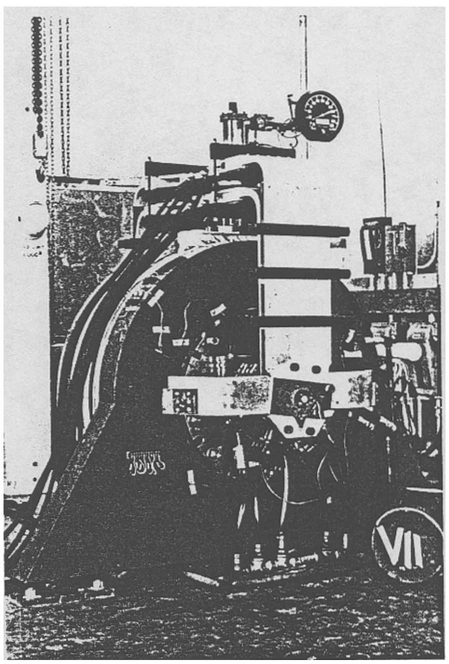


Figure 1. 5 MJ homopolar generator (1974)

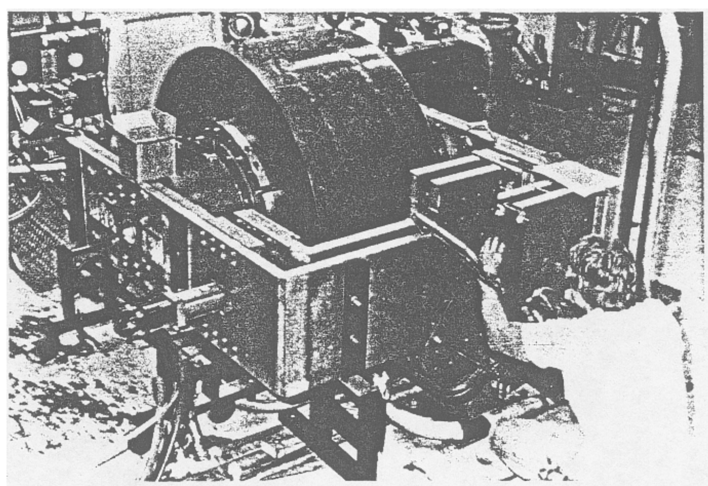


Figure 2. Upgraded (10 MJ) homopolar generator (1980)

PRINCIPLES OF HPG OPERATION

Although the homopolar generator can be constructed using several different geometries [10], the simplest form is the disk, shown schematically in Fig. 3. Energy is stored kinetically in a cylindrical rotor by motoring it to a high speed. The rotor is surrounded by a ferromagnetic back-iron that contains a field coil coaxial with the rotor. When excited, the coil creates a magnetic flux through the back-iron, air gap, and rotor. Thus the elements of rotor mass constitute an electrical conductor moving orthogonally to a magnetic field, and an electrical potential gradient is developed between the shaft and the circumference of the rotor. Sets of sliding brushes at each end of the shaft and at the circumference serve to connect the rotor to the external load circuit, which may include a making switch.

The voltage at the HPG terminals (*V)* is proportional to the angular velocity of the rotor (ω) and to the magnetic flux (ϕ):

$$V = \frac{\omega\phi}{2\pi}$$

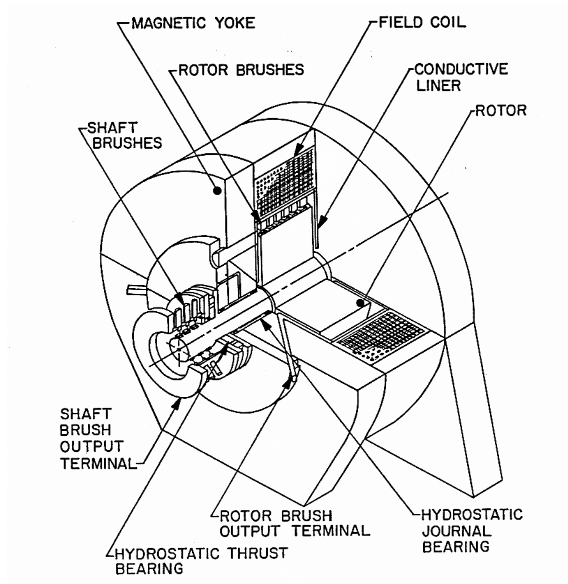


Figure 3. Schematic drawing of disk-type HPG

Compared to conventional ac generators, this voltage is typically low. The maximum design voltage for the 10-MJ HPG, for example, is 45 V.[9] The low internal resistances of the massive rotor and shaft result in very high current capability, however. Thus, an HPG with energy storage of 10 MJ is capable of discharge pulses having peak power levels of about 30 MW.

Electrically, an HPG models as a very high capacitance. The equivalent capacitance can be calculated by equating the kinetic mechanical energy to the corresponding electrical energy:

$$C = \frac{2\pi^2}{\phi}$$

where *J* is the polar moment of inertia of the rotor. Thus, the discharge pulse of the HPG (either current or voltage) into a resistive load such as a weld consists of a rapid current rise to a peak value followed by a first-order exponential decay to zero. This decay has a time constant (τ) given by

$$\tau = \frac{1}{RC}$$

In typical welding applications, the output circuit resistance is usually dominated by the (time-varying) resistance of the workpieces and the weld interface, while the circuit capacitance is almost entirely concentrated in the HPG. Figure 4 shows the output circuit of the 10-MJ HPG.

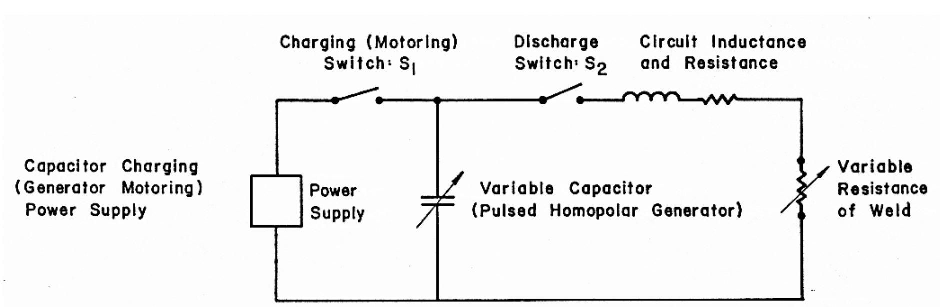


Figure 4. Schematic drawing of 10 MJ omopolar generator output circuit for a homopolar pulse welding system

PRINCIPLES OF HOMOPOLAR PULSE WELDING

Homopolar pulse welding (HPW) is an upset welding process that uses the unidirectional HPG current pulse to heat preferentially the interface between two workpieces which are lightly loaded mechanically but are in solid contact, and then increases the axial force to forge the workpieces together without melting them. The time variation of the various HPW parameters during a typical weld is shown in Fig. 5.

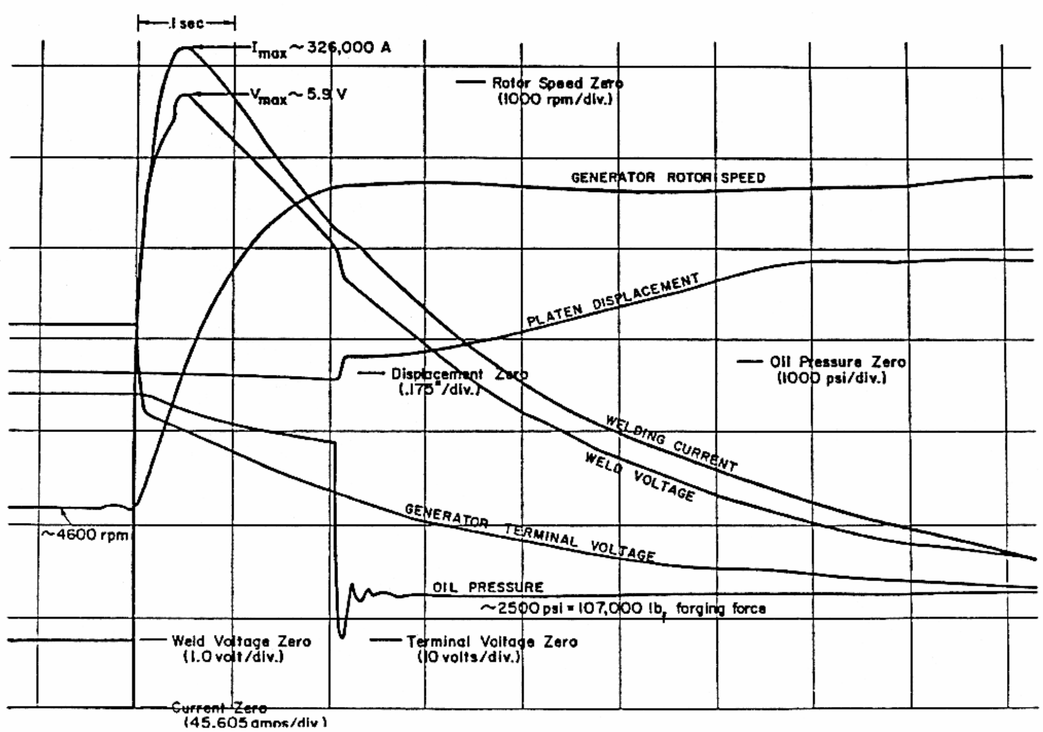


Figure 5. Parameter variations during a typical homopolar pulse weld

Heat generation is initially concentrated at the interface due to constriction resistance at the faying surfaces. Interface pressure is kept low early in the pulse to maximize the I^2R heating caused by the contact voltage drop. Ideally, the interface and the adjacent bulk material will have been heated to forging temperature just as the pressure is increased. The workpieces continue to upset either to material refusal or until a mechanical stop in the tooling is reached. The amount of upset is typically between 0.20 and 0.25 in. (0.5 and 0.6 cm), regardless of the weld cross-section.

Because of the proximity of the electrical contact leading edges (located as close as 0.5 in., or 1.3 cm, on either side of the interface), the heat-affected zone is small compared to that obtained using many other processes. The comparatively high heating and cooling rates and the short time at weld temperature minimize grain growth and undesirable metallurgical reactions. Finally, because of the unidirectional nature of the pulse, current distribution and the resulting temperature distribution are relatively uniform over the cross-section, so that large, irregular sections can be successfully welded.

PAST RAIL WELDING EFFORTS USING HPW

In 1980, NSF sponsored research by UT-CEM in the feasibility of using HPW in joining a wide variety of engineering alloys.[6] One task in this project involved joining irregular shapes, to test for uniformity of current distribution. One such test involved mild steel 16 lb/yd mine train rail, shown as-welded in Fig. 6. Subsequently, NSF and others sponsored a major research project to study HPW joining of high-carbon railroad rail and certain vehicle components. [1]

The 90 lb/yd rail, as shown in Fig. 7, having a carbon content of about 0.8 percent C, was welded using the 10-MJ HPG. The welding fixture and generator, with connecting busbars, are shown in Fig. 8. Typical rail welding parameters are given in Table 1. Appearance of an as-welded 90 lb/yd rail is shown in Fig. 9.

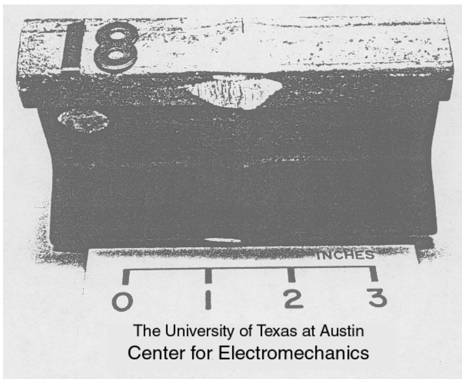


Figure 6. Visual appearance of homopolar pulse weld in 16 lb/yd rail

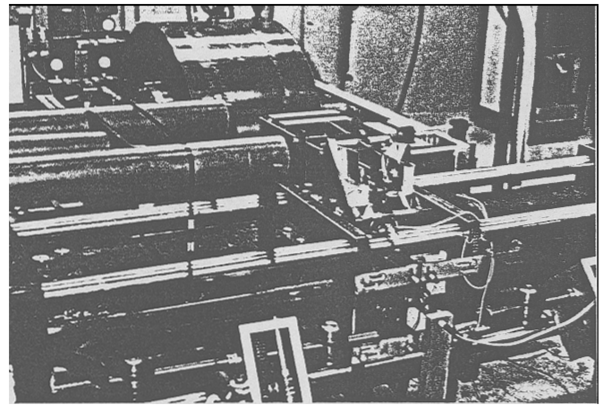


Figure 8. Rail welding fixture attached to 10 MJ homopolar generator

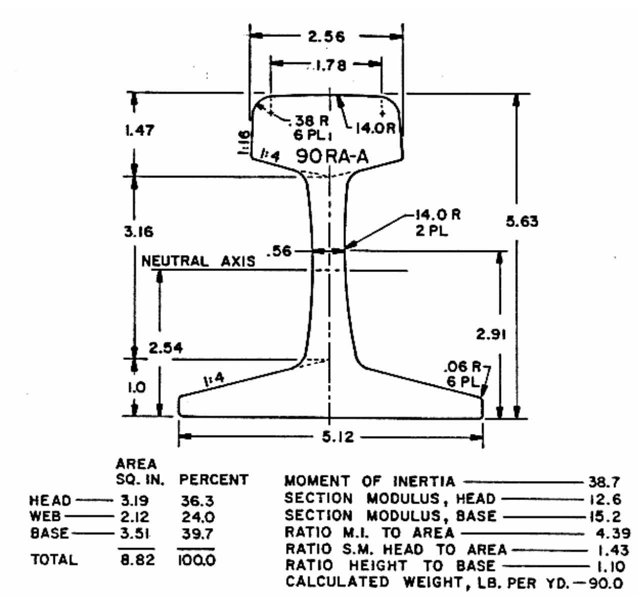


Figure 7. Section shape and properties of 90 lb/yd rail

Table 1. Average HPW rail welding parameters

Parameter	Value	Units
Peak current	575	kA
Peak voltage	23	V
Current rise time	85	ms
Pulse duration	3.2	s
Weld zone energy density	0.15	MJ/in2
Initial pressure	6,000	lb/in.2
	41.3	MPa
Upset pressure	34,000	lb'/in.2
	234.5	MPa
Time to upset	640	ms

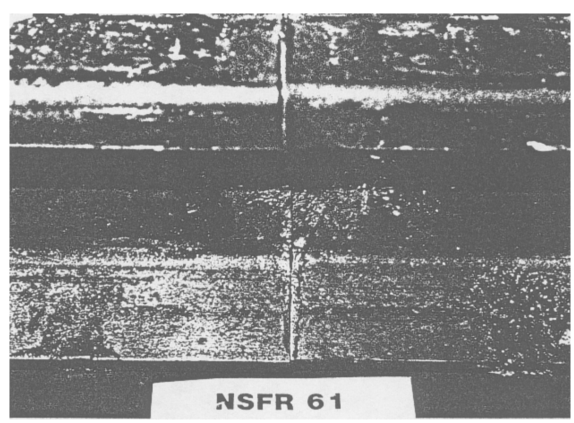
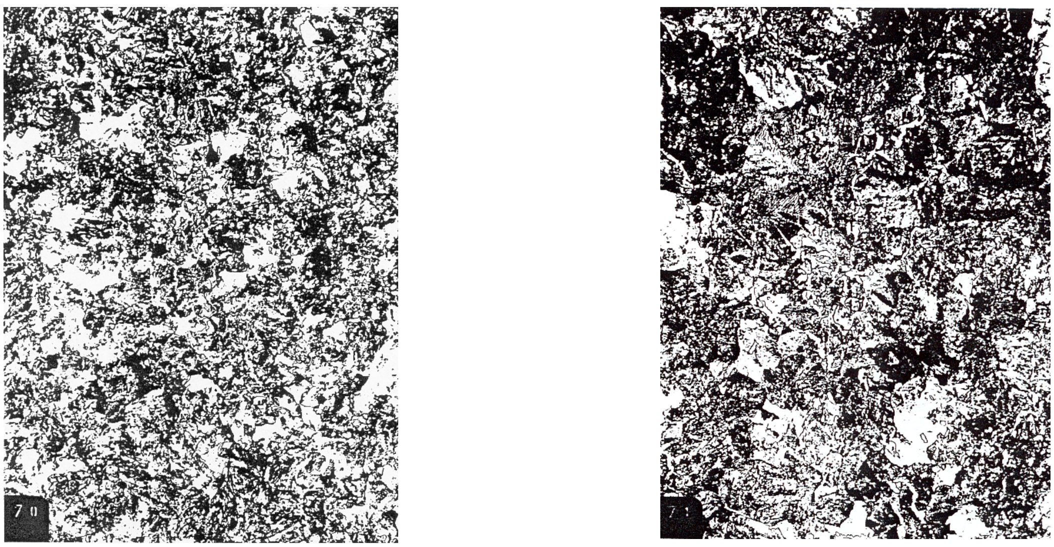


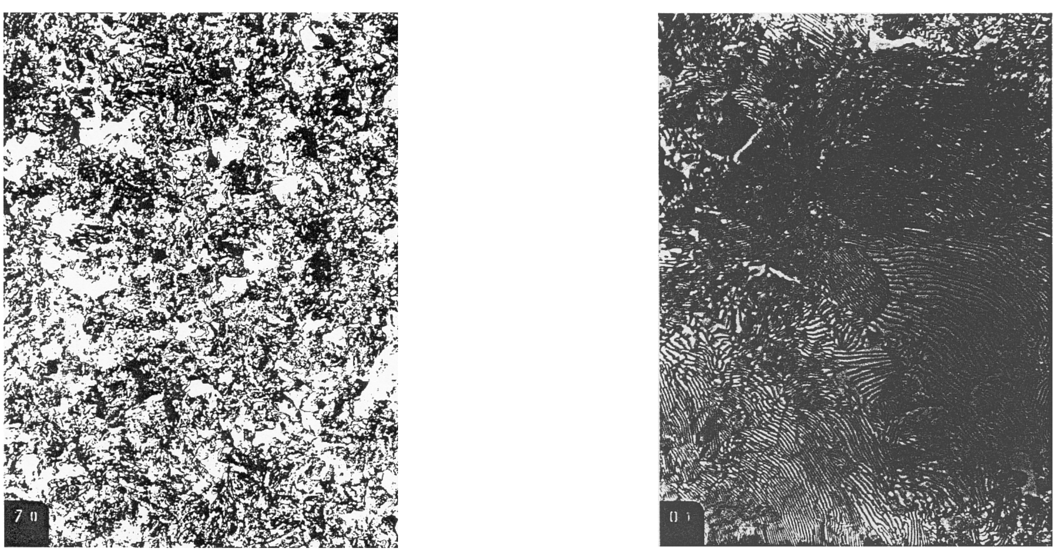
Figure 9. Visual appearance of early homopolar pulse weld in 90 lb/yd rail

Photomicrographs of the weld line in a typical welded rail are presented in Fig. 10. As is usually the case in homopolar pulse welds, the weld line is inconspicuous, but can be detected by the local presence of some alpha veining (ferrite regions) in boundaries of pearlite grains. Presumably, the veining resulted from some superficial decarburization that occurred on the faying surface early in the weld heating cycle, within the second or so before coalescence took place. There was substantial grain refinement in these welds, as can be seen by comparison with the parent metal microstructure (Fig. 11). The grain refinement should be beneficial to the properties of the weld. The weld microstructures, apart from the veining, consist of fine pearlite and possibly some bainite, which indicates that the cooling rates at 1,300°F (700°C) were between about 900 and 1,800°F/min (500 and 1,000°C/min). It was encouraging to note that these natural cooling rates are sufficiently low that martensite does not form in the weld zone. This is consistent with our observations of in-plant flash welding of similar rails, in which the welds were being allowed to cool naturally. We conclude that in homopolar pulse welding of carbon steel rails, martensite is not likely to create a problem. If this conclusion should prove to be in error, there are means for controlling the cooling rates of welds by controlling generator excitation during the pulse.



(a) X 200 (b) X 800

Figure 10. Microstructure of weld line in HPR welded rail (Weld NSFR 61 – Etch: Picral)



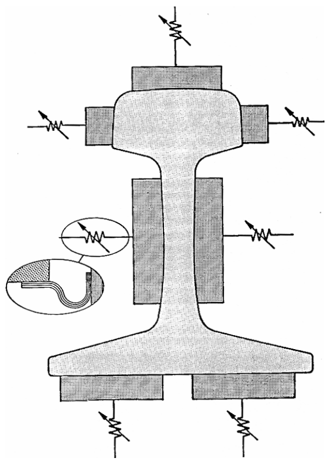
(a) X 200 (b) X 800

Figure 11. Microstructure of parent rail steel (Etch: 2% Picral)

Physical testing of these rails included full-scale, three-point guided bend tests. Then tests resulted in breaks that originated outside the heat affected zones of the tested rails. Furthermore, maximum hardness was 293 Brinell or 31 Rockwell C, as shown by microhardness traverses across the weld zones of typical welds, confirming that there was no martensite formation [1].

Although the metallurgical and physical properties of the welded rail appeared quite good, some special problems arose with regard to the experimental tooling. Specifically, efficient current delivery into the rails, and mechanical gripping and alignment of the rails proved to be quite difficult.

Experience has shown that the welding electrical contacts need to be clamped onto the smooth, scale-free surface of the workpiece with a minimum pressure of about 4,000 lb/in.^{2}. Otherwise, the contact voltage drop at the electrical contacts/workpiece interface can result in sufficient local heat generation to damage the member (generally the workpiece) that has the lower thermal conductivity. The possibility of local overheating of the workpiece is greater for irregular sections, in which less peripheral length is available for electrical contact placement. For the subject rail, the electrode arrangement used is illustrated in Fig. 12. The electrical contacts were rectangular chromiumcopper blocks 2.0 in. (5 cm) long. This geometry resulted in a nominal electrical contact area current density of 25 kA/in.^{2} (3.1 kA/cm^2) and a leading edge linear current density of 58.2 kA/in. (22.9 kA/cm), higher by factors of 2.5 and 3.5, respectively, over those used in previous welding of pipe [5].



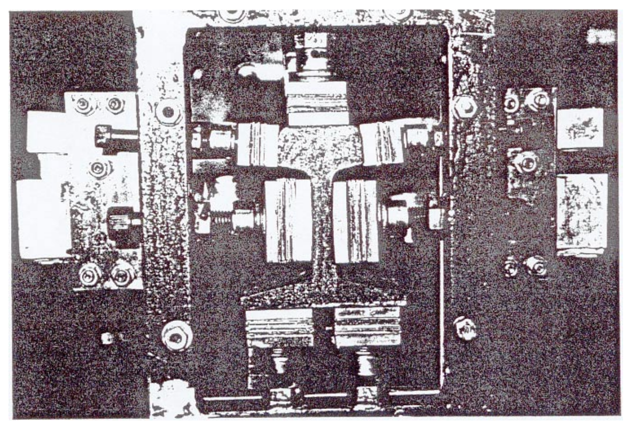


Figure 12. Electrical contact arrangement for rail welding at UT-CEM

These relatively high current densities caused surface hot spots under the electrical contacts on several weldments that were subsequently quenched at martensite-forming rates by adjacent (cold) copper and steel. Such a martensite island acted as a crack initiator in one of the full-scale bend tests.

Other problem areas with the fixture were mechanical clamping and maintaining rail alignment during and after welding. A drawing of the rail welding fixture is shown in Fig. 13. Two high-pressure hydraulic cylinders were used to provide axial force. The lead screw-actuated gripping cams proved to be inadequate for reacting against the high upset force (approximately 250,000 lbf (1.1 MN), however, so the rail workpieces were deadheaded with end plates. Furthermore, the 29 in. (75 cm) unsupported length at the joint was great enough to cause buckling in the hot, plastic weld zone, adversely affecting weld alignment. Finally, manual loading and unloading of the fixture was very tedious, resulting in long turn-around time.

The rail welding project was completed in 1981. Since then, UT-CEM has been continuously engaged in funded research in pulse power industrial applications. The 10 MJ HPG has delivered hundreds of discharges at current levels as high as 800 kA, with the same brushgear and only limited maintenance. The old motoring system was replaced in 1983 with a new 400 hp, 6,000 lb/in.^{2} (300 kW, 41 MPa) hydraulic power supply.

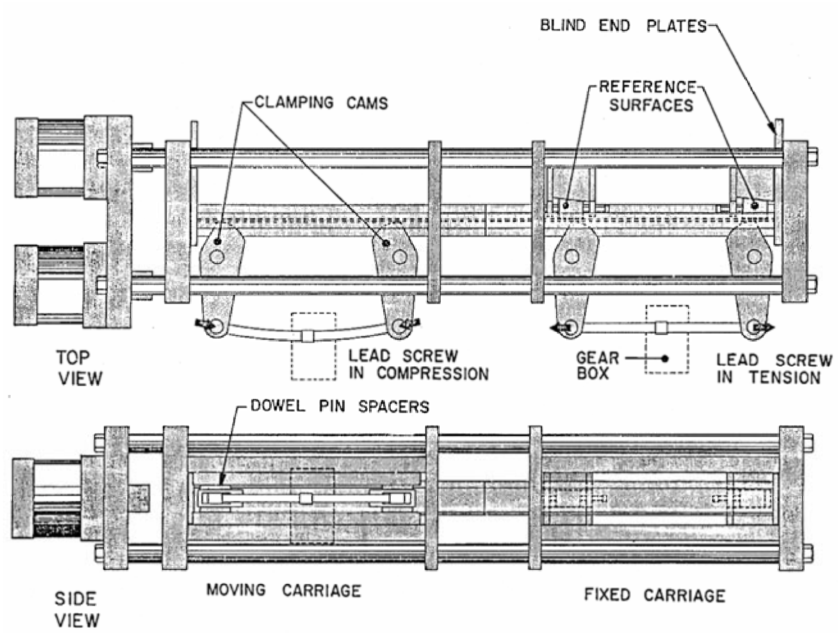


Figure 13. Layout of rail welding fixture

HOMOPOLAR PULSED WELDING FIXTURE DESIGN ADVANCES

OIME, Inc., has designed, developed, and demonstrated a homopolar pulse welding fixture which addresses and solves the problems identified in the NSF rail welding program conducted by UT-CEM. This fixture is capable of welding tubular products having outside diameters in the 6.625 to 7.625 in. (16.8 to 19.3 cm) range [13], cross-sectional areas from 6 to 12 in.^{2} (38 to 77 cm^2), and has been used to produce successful demonstration welds of 6.625 in. OD x 0.437 in. wall (16.8 x 1.1-cm) API X-52 line pipe with a cross-section of 8.5 in.^{2} (54.8 cm^2). The major problem areas that were addressed in the design of this fixture were

- insufficient electrical contact-to-workpiece interface pressure
- workpiece burning under the leading edges of the electrical contacts
- insufficient mechanical gripping force
- prevention of buckling of the hot workpieces between the mechanical grips
- improving rigidity of alignment of the workpieces

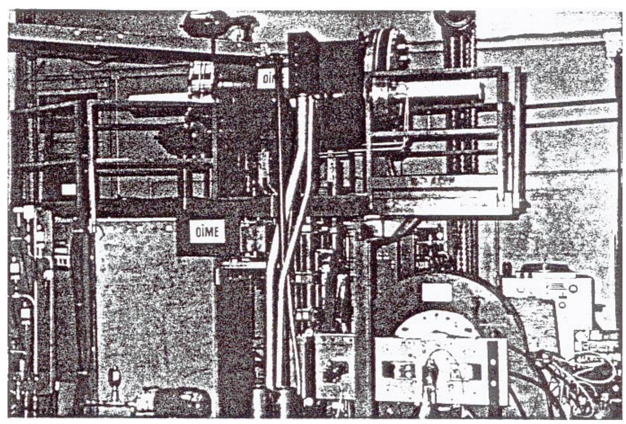


Figure 14. 10 MJ homopolar generator and OIME, Inc., pipe welding fixture

The solutions to each of these problems as applied to pipe welding are described in this section.

ELECTRICAL CONTACT PRESSURE

The contact pressure between the electrical contacts and the workpieces is very important in the HPW process. Large current pulses on the order of 70 kA/in.^{2} of weld area (10 kA/cm^2) are fed through the contact surface between the workpiece and the electrical contacts. Currents of this magnitude require high gripping pressures to prevent excessive workpiece heating under the contacts. On the NSF rail welding fixture designed and built by UT-CEM, the total contact area between the workpieces and the electrodes was 23.75 in.^{2} (153 cm^2) for approximately the same weld area as in the OIME pipe welder. For a weld current of 70 kA/in.^{2} x 8.5 in.^{2} or 595 kA, the average current density under the contact would have been 25 kA/in.^{2} (3.9 kA/cm^2). This high current density plus the somewhat inefficient method of loading the contacts against the rail led to some local overheating of the workpieces under the contacts. Estimated clamping pressures achieved in the NSF fixture are about 1,500 lb/in.^{2} (10 MPa).

The OIME fixture has significantly increased electrical contact area and clamping pressure between the electrical contacts and the workpieces. The total electrical contact area was increased to 92.8 in.^{2} (235 cm^2) for the same total weld current, thereby decreasing the current density under the electrical jaws to 6.4 kA/in.^{2} (1 kA/cm^2). The electrical contact clamping actuators, although of similar design to the NSF fixture clamps, are larger and more rigid. On the OIME fixture each of the six electrical contact shoes has an area of 15.5 in.^{2} (100 cm^2) and is actuated by a single 1-8 UNC socket-head cap screw. Torquing of these bolts to their rated seating torque of 1,000 lb-ft (1,350 N-m) generates an axial force of 70,300 lb (313 kN), which corresponds to an electrical interface contact pressure of 4,500 lb/in.^{2} (31 MPa). It was found that this amount of contact pressure was not needed with the dual-material contact shoes, discussed in the next section, and that the contacts required only 300 lb-ft (400 N-m) of torque to function properly.

LEADING EDGE CONTACT BURNING

The next problem area the OIME pipe welding fixture addressed was workpiece burning under the leading edge of the electrical contacts. In earlier welding fixtures, the contacts were copper blocks clamped onto the workpiece surfaces. When a weld is made, the discharge current from the HPG would flow from one set of electrical contacts into the workpiece, across the weld interface, into the second workpiece, and then out through the second set of electrical contacts. The current naturally tries to flow through the path of least resistance, and so it would remain in the lower-resistance electrical contact material for as long as possible. This caused the current to enter the workpiece primarily along the leading edge of the electrical contact shoes, i.e., the edge closest to the weld interface. This caused very high current densities at these leading edges. It was determined through previous experience with other welding fixtures that leading edge contact burning can be prevented if the leading edge current density (the total peak weld current divided by the linear dimension of the leading edge of the contact) is kept below 20 kA/in. (8 kA/cm). Comparing this value to the calculated leading edge current density in the NSF rail welding fixture of over 50 kA/in. (20 kA/cm) predicts that there would be considerable leading edge burning. Some burning did occur during the NSF rail welding program. Assuming that the electrical contact on the 6.625 in. OD pipe to be welded in the OIME fixture could be designed to utilize about 89% of the pipe circumference of 20.8 in. (53 cm), leading edge current density would be 32 kA/in. (13 kA/cm). This value, although lower than the one predicted in the NSF rail welding project, is considerably higher than the desired maximum value and led us to believe that we had a potential contact leading edge burning problem.

The solution to this problem was to design and build a set of electrical contacts that would force the current to enter the workpiece uniformly under the contact area, or at least to enter the workpiece at more than one effective leading edge. The designs to accomplish these two solutions are shown in Figs. 15 and 16. Figure 15 shows a design that would cause the current to enter the workpiece uniformly under the electrical contact. The variable resistance material shown in this design is not currently commercially available, however. It appears feasible to manufacture a material of this sort by using variable-composition powder metal technology. It also appears possible to manufacture this material centrifugally casting a metal alloy with different density constituents such as copper and tungsten. For welding 6 in. API X-52 line pipe with a resistivity of 19 μΩ-cm a 5 in. (13 cm) long variable-resistance sleeve with a low-end resistivity of 2 μΩ-cm would need to increase to about 73 μΩ-cm. These resistivity levels correspond to the resistivity of ETP copper and 304 stainless steel, respectively.

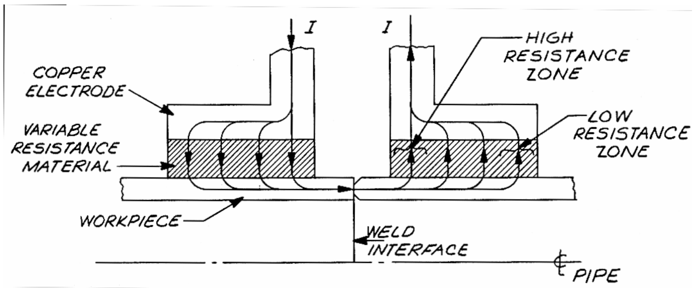


Figure 15. Graded-composition electrical contacts

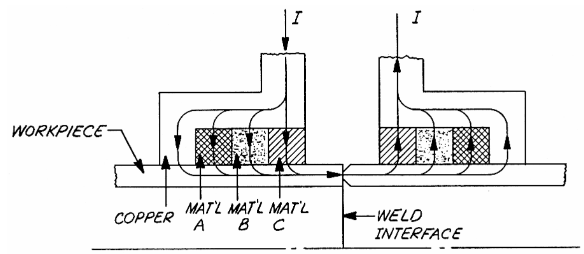


Figure 16. Segmented electrical contacts

Figure 16 shows a practical method to approximate the design depicted in Fig. 15. The number of different-resistance materials required would be determined by the required number of effective leading edges needed to achieve the 20 kA/in. maximum allowable leading edge current density. From previous calculations, in order to decrease the 32 kA/in. current density predicted for the X-52 pipe to less than the desired 20 kA/in., two effective leading edges would be necessary. Using equal areas of the two different-resistance materials and choosing ETP copper as the lower-resistance material, leads to a desired resistivity in the high resistance material of 309 μΩ-cm. This resistivity is too high for commonly available materials, so the design was modified to have unequal areas of the materials. The area ratio of 4 to 1 was chosen for the low-resistance material to high-resistance material ratio. This led to a required resistivity of 123 μΩ-cm in the high-resistance material, which corresponds to the resistivity of Hastelloy F. This differential area design increases the current density under the high-resistance material to 14 kA/in.^{2}, which was still well under the 25 kA/in.^{2} seen in the NSF rail welding fixture, and which proved to be satisfactory. Testing of this design showed no evidence of contact burning under the leading edge of the electrical contacts.

MECHANICAL GRIPPING

Homopolar welding of continuous length workpieces, such as pipe or rail, requires that the workpiece be rigidly gripped tightly enough to transfer the forging force necessary to complete the weld into the workpiece through a frictional grip. Previous welding fixtures attempted to do this with mechanically-set clamps, but were unsuccessful [1,6]. These weld fixtures required the use of short deadheaded workpieces before they could produce satisfactory welds. Typical forging pressures of 20,000 to 30,000 lb/in.^{2} (140 to 200 MPa) across the full weld cross-section produce welds of excellent quality. This forging pressure yields forging forces on 8.5 in.^{2} (55 cm^2) of weld area of 170,000 to 255,000 lb (750 to 1,000 kN). These forces must be communicated from the welding fixture to the workpiece without damaging it.

The solution to this problem was to incorporate the time-proven slip designs used in the oil industry for gripping pipes and casing. These slips typically use multiple rows of serrated-tooth dies set into self-actuating wedges. When used in the oil field, these slips are set by dropping them around the pipe and into a tapered bowl. This design causes the force that is being held to actuate the slips. The harder one pulls on the pipe, the tighter the slips grip. Typical slip ratings for 6.625 in. OD pipe are 375 and 500 ton (3.3 and 4.4 MN) load capacities. The design to incorporate this technology into a pipe welding fixture (that will also be used for a rail welding fixture; see Figs. 17 and 18), used 48 gripping blocks (A) set into six separate slip wedges (B) to grip each workpiece. These six slip wedges were radially compressed against the pipe by a hydraulic wedging ring (C). The force from the hydraulic upsetting cylinder was transferred into the slip wedges through a bearing ring (D) to prevent the forging force from creating excessive hydraulic pressures in the actuating cylinder. The slip wedge design worked very well and has been tested to forces in excess of 500,000 lb (2.2 MN) with surface marking on the pipe being less than 0.030 in. (0.75 mm) deep. This design has eliminated the problem of mechanical grip slippage that was seen in earlier weld fixture designs.

WORKPIECE BUCKLING

Another problem area which the OIME welding fixture successfully addressed was that of buckling of the workpiece between the mechanical grips during the forging action. This problem was seen on the NSF rail welding fixture and occurred for two reasons. The first was that the NSF fixture used dual off-axis hydraulic cylinders to generate the forging force. The forces produced by these cylinders could not be guaranteed to be of equal magnitude, especially during the dynamic portion of the forging action. Consequently, there was a possibility of eccentric loads on the workpieces. Such eccentric loads can cause the onset of buckling at lower loading values than those predicted for axial loads. The second difficulty with the NSF rail welding fixture arose from the relatively large distance between the mechanical clamps and from the lack of any rigid lateral restraint of the workpieces between these clamps. Assuming an effective diameter of the rail to have been about 5.5 in., then the 29 in. length between the mechanical clamps gave a column L/D ratio of 5.27 to 1.

The solution to this buckling problem was accomplished on the OIME pipe welding fixture by three design features. The first was to use a single annular upsetting cylinder with the workpiece located on the centerline of the cylinder. This eliminated any possibility of eccentric forging forces on the workpieces. The second feature was to close-couple the mechanical clamps. The distance between the clamps on this fixture is only 17 in. (43 cm), which corresponds to a column L/D ratio of 2.6 to 1 for the 6 in. pipe. The mechanical grips themselves were also designed to have a relatively large L/D ratio of 2.1 to 1, thereby providing a rigid cantilever support of the workpiece. The third thing that was done to prevent workpiece buckling between the mechanical clamps was to make the electrical clamps radially rigid, thus providing significant lateral restraint to the workpieces between the clamps. These methods solved the problem of workpiece buckling.

MECHANICAL ALIGNMENT

The problem of maintaining good mechanical alignment of the workpieces during the welding process is closely related to the problem of preventing eccentric workpiece loading and subsequent buckling. The solution is to provide a rigid lateral positioning and support structure for the workpieces that will still allow for the axial motion required during the forging action. This was accomplished by several of the design innovations described earlier, including

- laterally rigid electrical contacts
- mechanical slips located and actuated by a annular wedge ring
- entire welding fixture enclosed within a single rigid case

Previous heavy-section welding fixtures such as the NSF rail welder relied on multiple precision-machined ways to provide lateral rigidity and still allow for axial movement. Although this type of design is functional, the relative lateral stiffness of the machined ways is much less than that of the heavy-wall large-diameter enclosure used to provide mechanical alignment in the OIME welding fixture. The use of these alignment solutions has produced a fixture which has shown no noticeable misalignment throughout the pipe welding program.

OIME RAIL WELDING FIXTURE

This section describes the proposed modifications which are going to be made to convert the OIME pipe welding fixture into a rail welder. The proposed rail welder (shown in cross-section in Figs. 17 and 18) is designed to produce full cross-sectional welds in 90 lb/yd rail road rail [14]. The cross-sectional area of this workpiece is 8.82 in.^{2} (57 cm^2), which is ideally suited to welding in this fixture. The only modifications required to be made to the pipe welding fixture to convert it into a rail welder are the manufacture of a new set of mechanical slip wedges designed to grip the rail shape, a new set of electrical contact jaws designed to accommodate the rail shape and its non-axisymmetric area, and a new electrical contact actuating mechanism to allow for automated control of this function.

MECHANICAL GRIPS

The mechanical grips used on the OIME rail welder, visible in Figs. 17 and 18, are very similar to the mechanical grips used on the OIME pipe welder described in the previous section. The same number of serrated-tooth gripping blocks will be used for welding 90 lb/yd rail as were used to weld the 6 in. schedule 80 pipe. The arrangement shown in Fig. 18 will incorporate four rows of four blocks per row on the rail head, web, and base. This gripping pattern will distribute the force throughout the rail section, as opposed to the original NSF rail welder which gripped only the web. Because the same ratio of gripping area to weld area is used between this welding fixture and the successful OIME pipe welder, mechanical gripping should be accomplished without the slipping problems previously encountered. Setting of the mechanical grips is done using the same tapered wedge ring method as was used on the pipe welder.

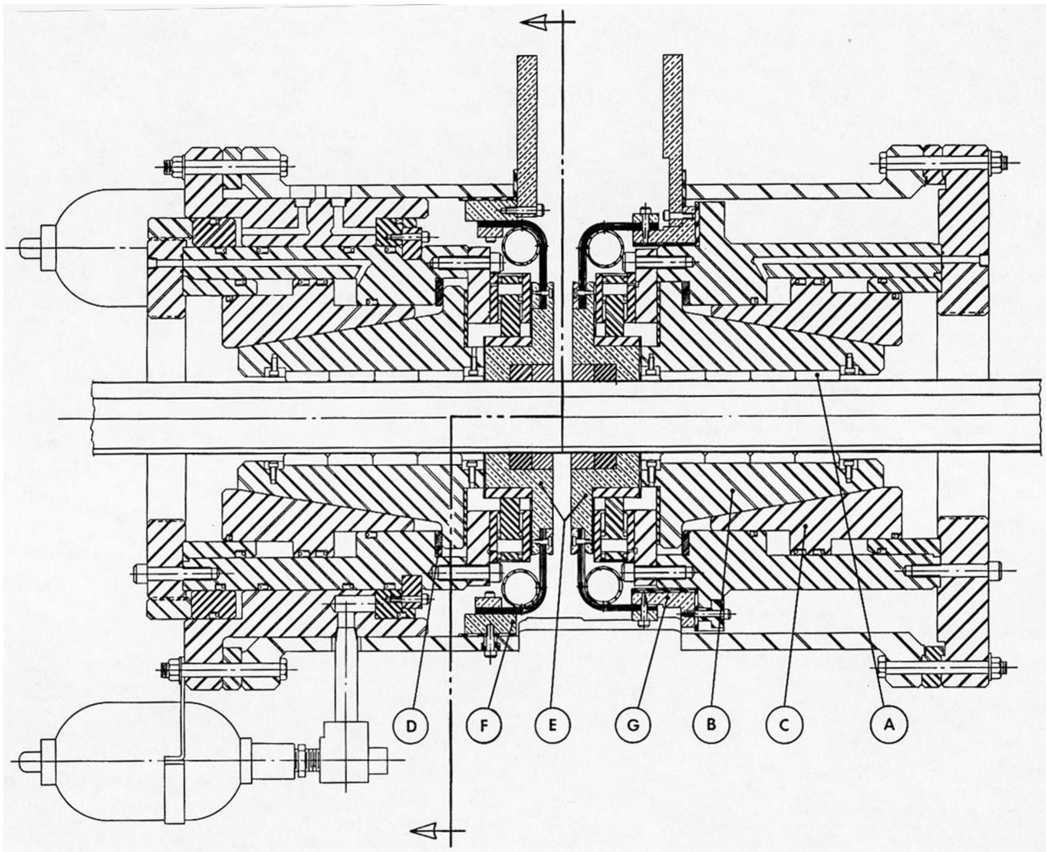


Figure 17. Longitudinal cross-section of OIME, Inc., rail welding fixture

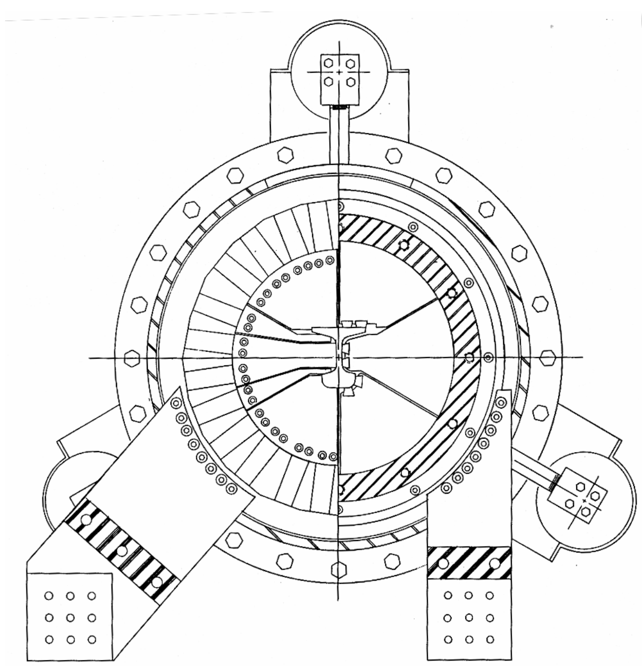


Figure 18. Transverse section of OIME, Inc., rail welding fixture

ELECTRICAL CONTACTS

The electrical contacts to be used on the OIME rail welder are also shown in Figs. 17 and 18. They are designed to have a leading edge perimeter of 15.95 in. (40 cm) and be 5.50 in. (14 cm) long. The expected maximum discharge current they will see is about 75 kA/in.^{2} (11.6 kA/cm^2) across 8.82 in.^{2} (57 cm^2) for a total of 661.5 kA. The contact area of each set of electrical contacts is 87.7 in.^{2} (566 cm^2), which would produce a current density on discharge of 7.5 kA/in.^{2} (1.2 kA/cm^2). This is 70%t less than the 25 kA/in.^{2} in the NSF rail welding fixture.

One potential problem that was identified during the design of these electrical contacts was leading edge burning. For single-material electrical contacts, the leading edge current parameter for this welder would have been 41.5 kA/in. (16.3 kA/cm), or about twice what we have specified as a design maximum. For this reason, it was decided to construct the three-material electrical contact shoe systems shown at (E) in Fig. 17. The measured resistivity of 90 lb/yd rail steel is about 18 μΩ-cm. Assuming an average radial thickness of 1.75 in. (4.4 cm) of resistive material, an axial length of 1.75 in. (9.4 cm), and a of 2.0 μΩ-cm, one can calculate that the required resistivity of stages 2 and 3 should be 66 and 129 μΩ-cm, respectively. These values correspond closely to the resistivities of Type 304 stainless steel and Hastelloy B, so these materials will be used to fabricate the electrical contacts for the OIME rail welder. These triple-material shoes will in effect give three leading edges, each 15.95 in. (40 cm) long, and will therefore decrease the leading edge current parameter to the acceptable level of 13.8 kA/in. (5.4 kA/cm). Because all three of the jaw materials have the same contact area with the workpiece, the current density for all three should remain at the 7.5 kA/in.^{2} value.

Two other design innovations incorporated into the electrical contacts of the OIME rail welding fixture involved the manner in which current is distributed to the various electrical contacts and the way the current is then passed into the workpiece. The current from the generator is distributed within the welding fixture through two heavy copper bus rings (Items F and G, Fig. 17). From these rings, the current passes to the individual electrical contacts through 48 bundles of copper straps. Each of these strap bundles (24 per workpiece) is a set of 50 copper straps 0.010 in. thick by 2.0 in. wide (0.25 mm x 5 cm). Four bundles feed current to each of the six individual electrical contact shoes on each end of the welding fixture. By adjusting the number of straps in a particular bundle, the current entering the workpiece in a particular area can be increased or decreased. This allows for field adjustment of the current distribution to insure uniform heating throughout the weld cross-section. The second design innovation concerned the method of passing current from the electrical contacts into the workpieces. Because of the differing cross-sectional areas of the rail head, web, and base, it was found during the NSF project that current had to be fed from the top side of the base and the sides of the head as well as from the more easily accessible areas. The OIME fixture is designed to use radial contact actuators, and it is very difficult to achieve the required electrical contact pressure in the less accessible regions using this radial actuation. This problem will be overcome through the use of two special electrical contacts that will be used to contact the sides of the rail web. These contacts will also feed current into the bottom of the rail head and the top of the rail base. Contact pressure on these two areas will be achieved through a wedging action. The portions of the electrical contacts that touch these areas are spring-loaded to apply the required pressure as a result of their radial action. All other features of the electrical jaws, such as rigid lateral workpiece restraint and high uniform contact pressure that were described earlier, will be retained in the OIME rail welder.

HYDRAULIC CONTACT ACTUATOR

The last major improvement that will be incorporated into the OIME rail welder is automatic hydraulic actuation of the electrical contacts. These contacts can be set and released from the welder control panel and require no manual manipulation before removal of the completed weld. Their function, is the same as in the section on the OIME pipe welder. In the rail welder, the 1-8 UNC socket-head cap screw used to actuate the electrical contacts on the pipe welder will be replaced with two high-pressure built-in hydraulic cylinders.

Each of the 12 electrical contact sections will be actuated by two 2.0 in. (5 cm) bore hydraulic cylinders. These actuators are designed to operate at 5,000 psi (34 MPa) and at this design pressure will produce 31,416 lb (140 kN) of electrical contact clamping force on each contact segment. The largest single-segment contact area on the rail welder will be 11.0 in.^{2} (70 cm^2), which corresponds to a contact pressure of 2,856 psi (19.7 MPa). From previous experience, this contact pressure across the large overall contact area of 87.7 in.^{2} (565 cm^2) should prevent the contact burning problems seen in previous weld fixture designs. Since each of the electrical segments in a contact set is a separate floating contact, this design will also allow a large dimensional variation in rail and will still produce good electrical contact over most of the rail surface.

CONCLUSIONS

Homopolar pulse welding has been studied as a metals joining process at the Center for Electromechanics, The University of Texas at Austin, for several years. The advantages of the process include a short welding time, uniform cross-sectional heat generation, and elimination of flux and filler requirements. UT-CEM successfully welded 90-lb/yd railroad rail in an earlier research program, but encountered fixturing problems. DIME, Inc., has designed and built an advanced welding fixture that has addressed these problems in welding API X-52 6 in. schedule 80 line pipe. Tooling has been designed to convert this prototype fixture to a field-portable 90 lb/yd rail welder. The process offers certain advantages over conventional means of upset butt welding of rail and could be a viable alternative to these processes in the relatively near future.

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